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TECHNICAL MEMORANDUM

A Stress Test for Determination of Certain Piezoelectric Properties of Small Piezoelectric Ceramic Rings

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14. ABSTRACT
Piezoelectricity is defined as pressure electricity. It is a property of polarized PZT (lead-zirconate-titanate) ceramic rings. As the name suggests, electricity is developed when pressure is applied to the rings. The reverse is also true. When an electric field is applied, the ceramic rings deform physically. The ceramic rings used do not have piezoelectric properties in their original state, however, piezoelectric behavior is induced when the rings are poled. The polarized rings are used in transducer stack constructions. A stress test, employing a Carver press, is performed on the piezoelectric ceramic rings in order to determine certain material parameters. The values of voltage, charge and capacitance are examined versus the static stress level on the ceramic rings. The information gathered is used to determine the variations of the material parameters d33, g33 and K33 with stress level.

15. SUBJECT TERMS
Piezoelectricity; pressure electricity; ceramic rings

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ABSTRACT

Piezoelectricity is defined as pressure electricity. It is a property of polarized PZT (lead-zirconate-titanate) ceramic rings. As the name suggests, electricity is developed when pressure is applied to the rings. The reverse is also true. When an electric field is applied, the ceramic rings deform physically. The ceramic rings used do not have piezoelectric properties in their original state, however, piezoelectric behavior is induced when the rings are poled. The polarized rings are used in transducer stack constructions. A stress test, employing a Carver press, is performed on the piezoelectric ceramic rings in order to determine certain material parameters. The values of voltage, charge and capacitance are examined versus the static stress level on the ceramic rings. The information gathered is used to determine the variations of the material parameters d_{33}, g_{33} and K_{33}^T with stress level.

INTRODUCTION

A Carver press was used to apply a one-dimensional stress (T_3) to the piezoelectric ceramic rings thereby producing an output voltage. This type of measurement was useful in that the constraints on the lateral motion of the ring due to the frictional forces of the Carver press platens are similar to the constraints imposed upon the ceramic in a transducer of end-mass design. In a transducer, the stack is prestressed in compression before being driven. One method used to apply stress to the stack is by torquing a nut on the tail-end of a stress rod. Such a method makes it difficult to measure the strain of the stress rod which, in turn, is used to calculate the stress in the ceramic stack. Thus, for greater ease and feasibility in taking measurements, each ring was stressed prior to stack construction. The charge release off the ring elements under such a stress was then determined. The values recorded from such an experiment allowed us to determine the material constants of each piezoelectric ceramic ring.

DISCUSSION

A diagram of the ceramic ring used is shown below.

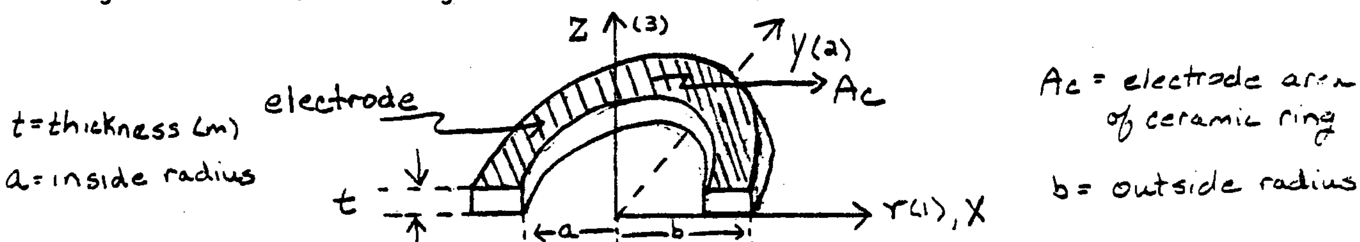


Figure I

Before beginning the experiment, the electrode area of the ceramic ring was calculated. Ring number 239 was chosen as our representative ring for all examples. The dimensions are as follows:

OUTSIDE DIAMETER = .0218 m
INSIDE DIAMETER = .0125 m
RING THICKNESS = 4.597×10^{-3}m
AREA = 2.50×10^{-4} m^2

When studying the propoerties of piezoelectric materials, it is necessary to formulate a standardized means for identifying directions. In figure I, numerals were assigned to the three different axes: 1 corresponding to the X-axis, 2 corresponding to the Y-axis and 3 corresponding to the Z-axis. In order to identify directions in piezolectric material constants, one or two numerical subscripts are added to a variable. In our study, for example, we examined the piezoelectric d_{33} and g_{33} constants. The d constant represents the ratio of a charge per unit area of an electrode that is perpendicular to a specified axis and which is perpendicular to the stress applied along the specified axis when all other stresses remain constant. d_{33} denotes the ratio of charge per unit area of an electrode flowing between two connected electrodes perpendicular to the 3 axis and to the stress applied along the 3 axis. The stresses in the 1 and 2 directions (T_1 and T_2) equal zero.

The g constant represents the ratio of strain developed along a specified axis to the electric charge per unit area of an electrode connected to two electrodes which are perpendicular to the specified axis. g_{33} denotes the ratio of strain developed in the 3 direction to the charge per unit area of an electrode perpendicular to the 3 axis.

Following from the above discussion, the essential equations are:

$$D_3 = q/A_C \quad (1)$$
$$E_3 = V/t \quad (2)$$
$$T_3 = F_A/A_C \quad (3)$$

Where:

V=Voltage (volts)
D_3=charge/Area (C/m^2)
E_3=volts/thickness (V/m^2)
T_3=force/area ($lbs./m^2$)
F_A=applied force (lbs.)
t=thickness (m)
A_C=area (m^2)

In our study, the inside and outside radial surfaces of the ceramic ring remained unloaded. As a result, $T_1 = T_2 = 0$ and consequently the aforementioned equations will hold for a one-dimensional stress only i.e. $T_3=F_A/A_C$. Given this situation, the strain in the 1 and 2 directions (S_1 and S_2) will not equal zero due to Poisson's ratio coupling which gives rise to lateral motion in the ring. For our studies, however, this is not of major importance.

In order to determine the type of measurement equipment required, the following values were calculated:

* 1) MAX. VOLTAGE (OUTPUT)

$V=g_{33}\,(t)\,(T_3)$ $\qquad g_{33} = 24.5 \times 10^{-3}$ Vm/N (PZT-8)

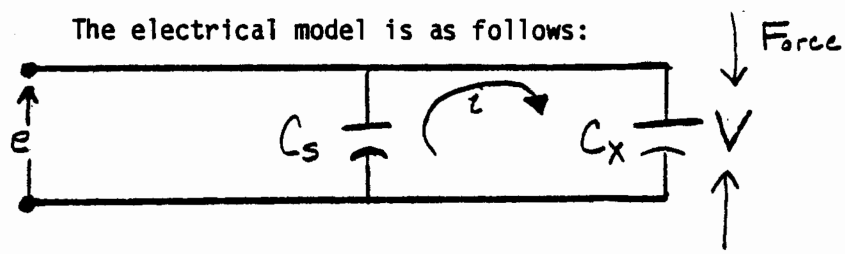
2) MAX FORCE (APPLIED F_A):

$F_A = T_3(A_C)$ $\qquad$ where T_3=5000 lbs./sq. inch (psi)

*assuming a stress, T_3, is at a level of 5000 psi

Values calculated from the above equations determined the force gauge requirements as well as the type of voltmeter to be used. F_A (maximum) was determined to be approximately 2000 psi. Vmax was approximately 4000 volts and was too high to be measured by a Keithley voltmeter. Thus, a voltage divider was used in conjunction with the voltmeter.

The electrical model is as follows:



Where:

e=measured output voltage
C_X=ceramic ring capacitance
Voltage=charge/capacitance
C_S=shunt capacitance
V=d.c. voltage

Applying a force to the ceramic ring produces a d.c. voltage (V) which was found to be:

$$V = q/C_X + q/C_S \qquad (4)$$

$$V = q((C_X + C_S)/C_X C_S) \qquad (5)$$

and the measured voltage was:

$$e = a/C_S = [VC_X C_S/C_S(C_X + C_S)] \qquad (6)$$

$$e = V(C_X/C_X + C_S) \qquad (7)$$

C_S was made to be significantly larger than C_X. Thus:

$$e = V\ (C_X/C_S) \qquad (8)$$

Therfore:

$$V = e(C_S/C_X) \qquad \text{and} \qquad q = e(C_S) \qquad (9) \text{ and } (10)$$

From these equations follows:

$$E_3 = V/t = e/t\ (C_S/C_X) \qquad (11)$$

and:

$$D_3 = q/A_C = e(C_S)/A_C \qquad (12)$$

A main problem existed, however, with the time constraint of the circuit. Because of internal electrical losses in the ceramic rings (Tan δ), the voltage generated by the applied stress decayed throughout the internal resistance path. Thus, a good lossless shunt capacitor was designed.

For our study:

$$C_S = 9.87 \times 10^{-6}\text{Farads} \qquad (13)$$

EXPERIMENTAL SET-UP

After all preliminaries had been carried out, each ring was tested individually. A diagram of the complete set-up is shown in figure II. The Carver press is a hydraulic pressure pump that lifts the bottom platen of the press to apply stress on an object. A calibrated gauge, mounted on the side of the press, shows the exact number of pounds being applied. The ceramic ring set-up (1) was inserted between the two platens of the press. The valve (2) on the hydraulic pressure pump was then closed. The bottom (movable) platen was manually pumped up (3) to apply the stress. The ring electrodes were attached to wires which led to the shunt capacitor (4). From the shunt capacitor, the output signal traveled to the voltmeter where the voltage was then determined. The amount of stress applied started at zero and was increased by increments of 500 pounds up to and including 2000 pounds. Thus, four voltage readings were recorded (500, 1000, 1500, 2000 lbs.). After each voltage reading, wires a and b (refer to FIG. II) were detached from the shunt

capacitor and then attached to the adjacent LCR meter in order to obtain a capacitance measurement. Once a capacitance measurement was taken, the wires were re-attached to the shunt capacitor.

For the experiment to work correctly, a non-conducting insert was needed for alignment (see FIG.III). For our experiment, several different ring insertions were needed before a suitable set-up was discovered. In all, sixteen rings were tested and in the initial debugging of the set-up six rings were broken. The first set-up consisted of two wire electrodes which were soldered onto opposite sides of the ring. Two spacer rings were used as insulators. This type of set-up was used for two channel rings. After all readings had been recorded, the ceramic ring insert was removed from the press. Upon attempting to remove the ring from its insert, the ring cracked. This situation applied to both rings. The fact that the electrodes were soldered directly on to the rings caused uneven stress loads, and therefore, caused the rings to break.

The next attempt used two electrodes constructed from a beryllium copper sheet. The electrodes were fastened with double sided tape to two stiff fiberglass squares acting as insulators. The ceramic ring was then placed between the squares resting fully on the electrodes. Three rings were tested in this manner. Unfortunately, all three broke while being stressed at or above the 1500 pound level. Such consistent breakage could be due to deficiencies in the ceramic ring itself or to improper alignment in the press.

In the next trial, one Channel and one Edo ring were used. The set-up consisted of the two beryllium copper electrodes, as before, fastened with double backed tape to two thin rubber squares. These squares were, in turn, fastened to the two stiff fiberglass squares. This type of set-up provided good results for the Channel ring. When testing the Edo ring, however, the extreme stress caused the ring to tear through the rubber and rest somewhat on the fiberglass. This caused severely uneven stress loads and the ring cracked.

In the following set-up, again, the beryllium copper electrodes were used. This time, one electrode was attached directly to the fiberglass square. The other electrode was fastened to a thick rubber square which, in turn, was attached to the fiberglass. Due to the thick rubber square's absorption of some of the applied force, lower output voltages were produced.

The final set-up consisted of the beryllium coper electrodes which were fastened to two slabs of lead. Two fiberglass squares, used as insulators, rested upon the lead pieces. This type of set-up provided the best results. Of the six rings tested, two were broken. The first casuality resulted from improper placement of the ring on the electrode causing uneven stress distribution.

Fig. II

EXPERIMENTAL
SET-UP

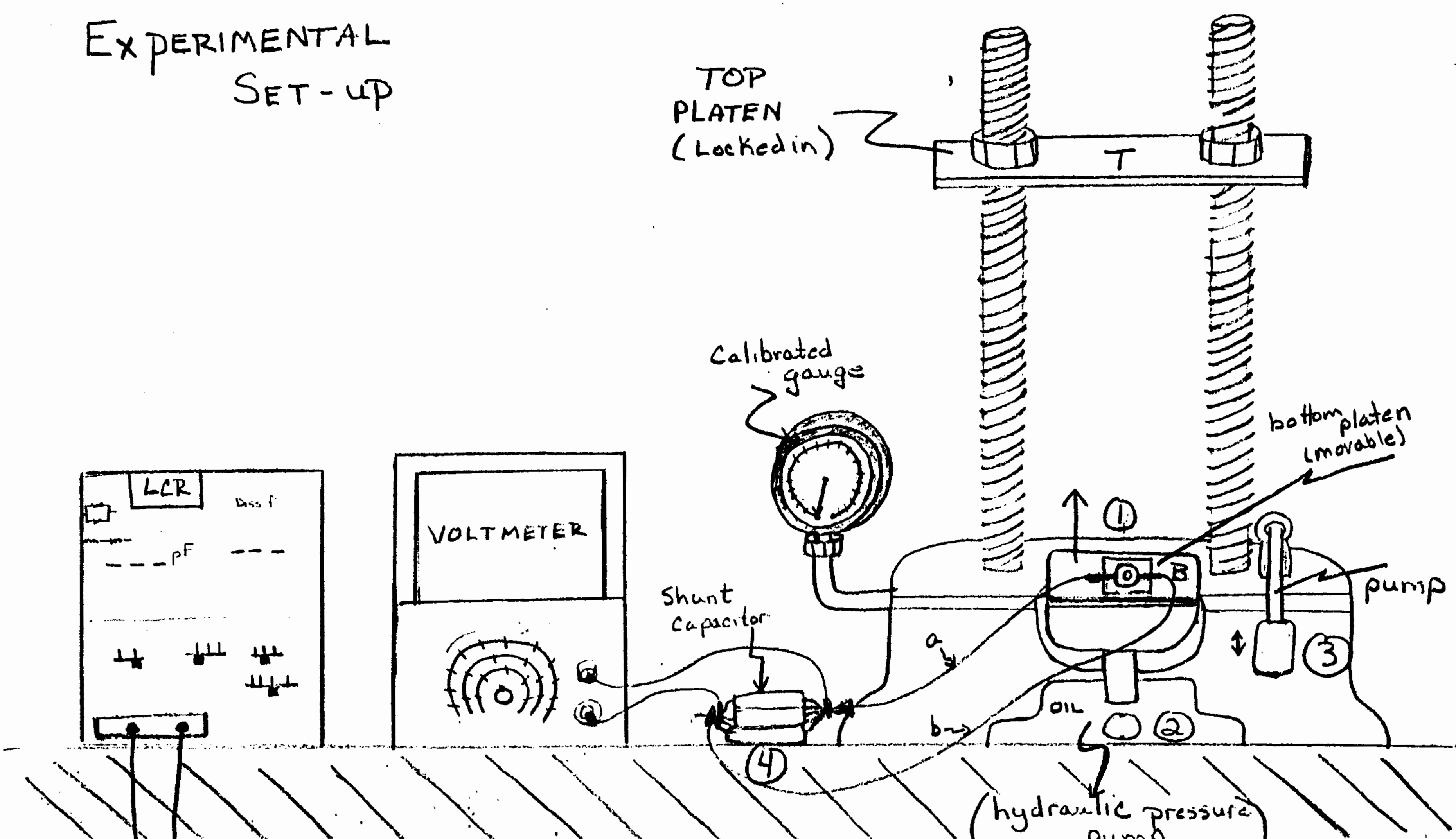
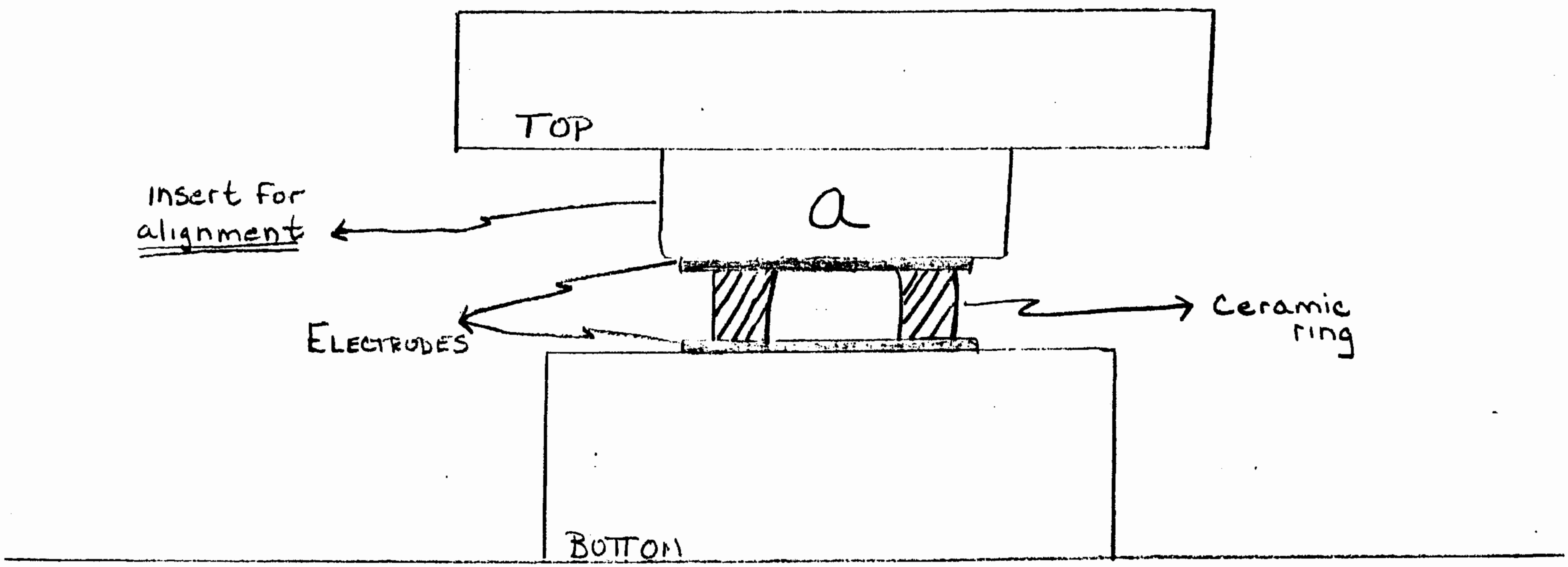


Fig. III

Ceramic ring insertion



RESULTS

Here are the recorded results of an average ring:

FORCE (N)	VOLTAGE (volts)	CAPACITANCE (pF)
2224	.056	454
4448	.120	498
6672	.193	540
8896	.287	556

Using equations (1) through (13), the following material parameters were calculated:

FORCE (Newtons)	CHARGE (C) ($\times 10^{-6}$)	D_3 (C/m^2) ($\times 10^{-3}$)	STRESS (N/m^2) ($\times 10^7$)	E_3 (V/m) ($\times 10^5$)
2224	.533	2.22	.89	2.66
4448	1.184	4.76	1.78	5.70
6672	1.91	7.64	2.67	9.17
8896	2.83	11.40	3.56	13.60

CONCLUSIONS

From the values generated, graphs were constructed which illustrate the relationship between the stress applied (T_3) and the calculated material parameters (see Appendix I). The first graph shows the relationship between the T_3 value and the E_3 value (volts/thickness).

As the graph illustrates, the slope of the curve near the origin determines the g_{33} constant of the ring:

$$g_{33} = E_3/T_3 = (V/t)(A_C/F_A) = (A_C/t)(V/F_A) \qquad (14)$$

As calculated, $g_{33} = 22.5 \times 10^{-3}$

We then compared the calculated value to the g_{33} constant value given for the ceramic rings.

GIVEN g_{33} VALUE = 24.5×10^{-3}
CALCULATED g_{33} VALUE = 22.5×10^{-3}

The percent difference was determined to be 8.2 percent.

The second graph represents the relationship between the T_3 value and the D_3 value (charge/Area). Again, by definition, the slope of the curve near the origin determines the d_{33} material constant of the ring examined:

$$d_{33} = D_3/T_3 = (q/A_C)(F_A/A_C)$$

Thus, $d_{33} = 239 \times 10^{-12}$

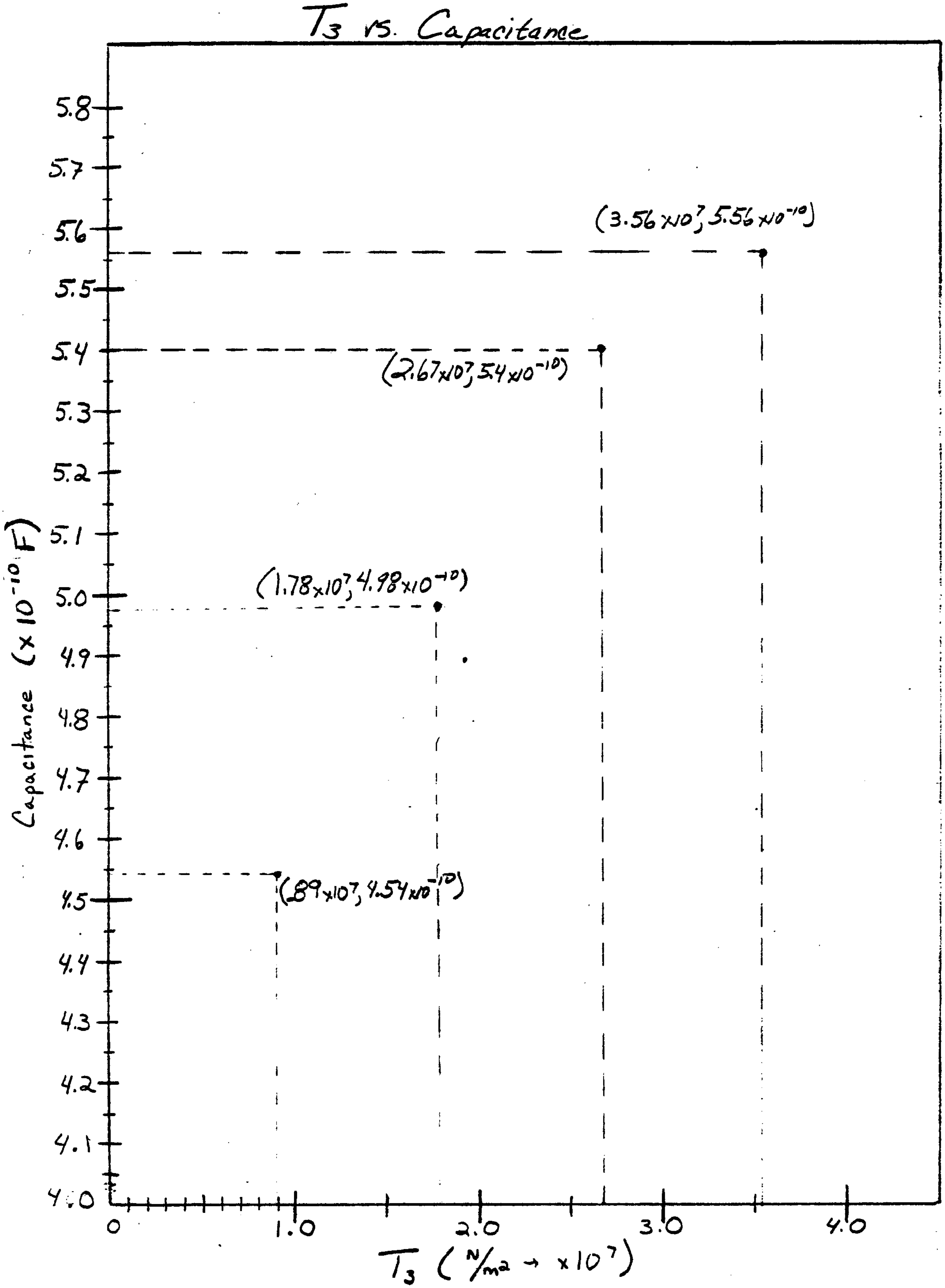
The d_{33} value obtained was compared to the d_{33} value recorded from the Berlincourt meter.

$$\text{Berlincourt value} = 220 \times 10^{-12}$$
$$\text{Experimental value} = 239 \times 10^{-12}$$

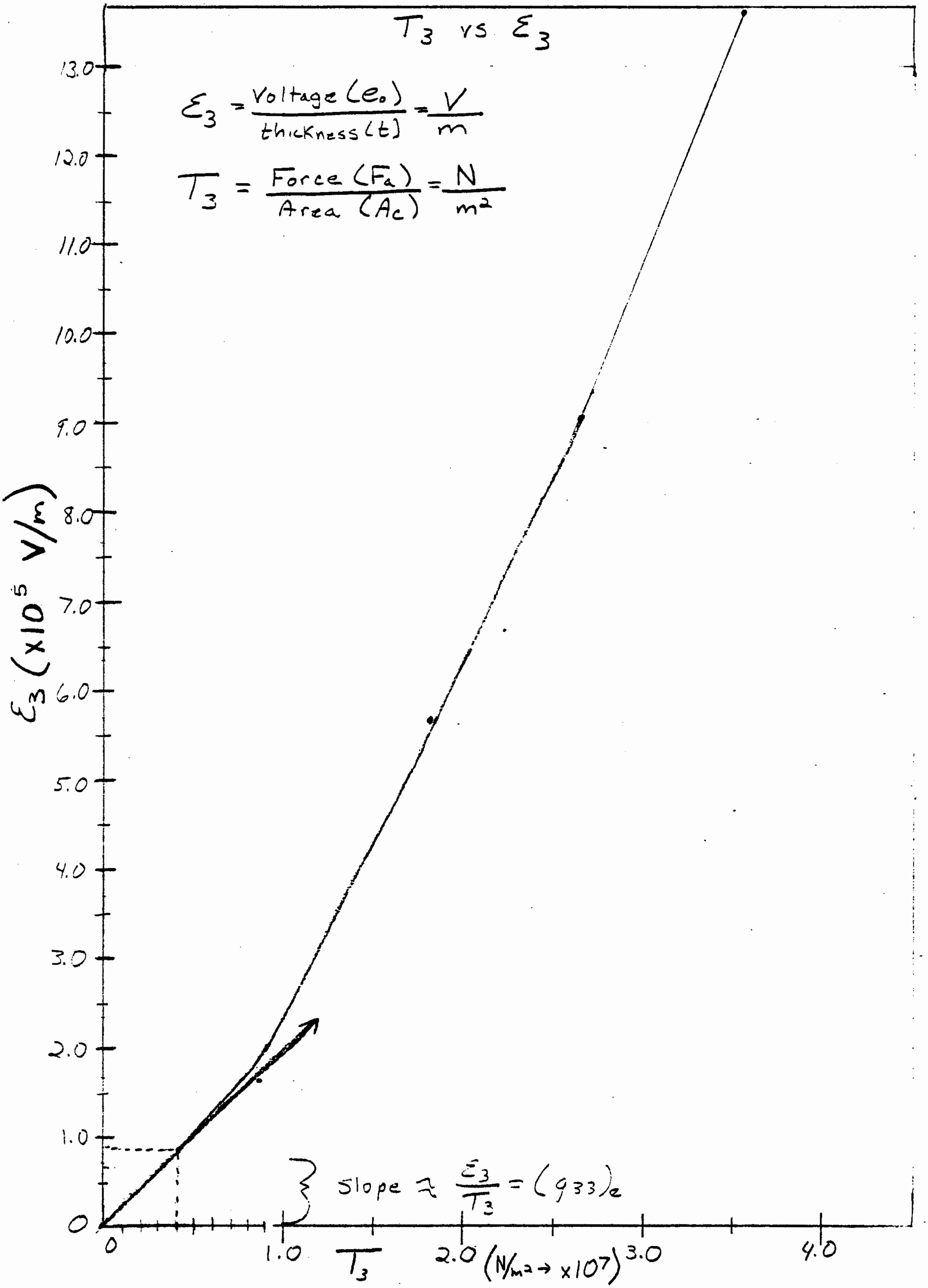
The percent difference was found to be 8.6 percent.

Calculating these g_{33} and d_{33} material parameters allows us to determine the relevant specifications needed in order to produce the ceramic rings. Taking into consideration the type of equipment with which the rings were tested and the trial and error method used, this experiment provided fairly accurate results. The complete test results are found in Appendix II.

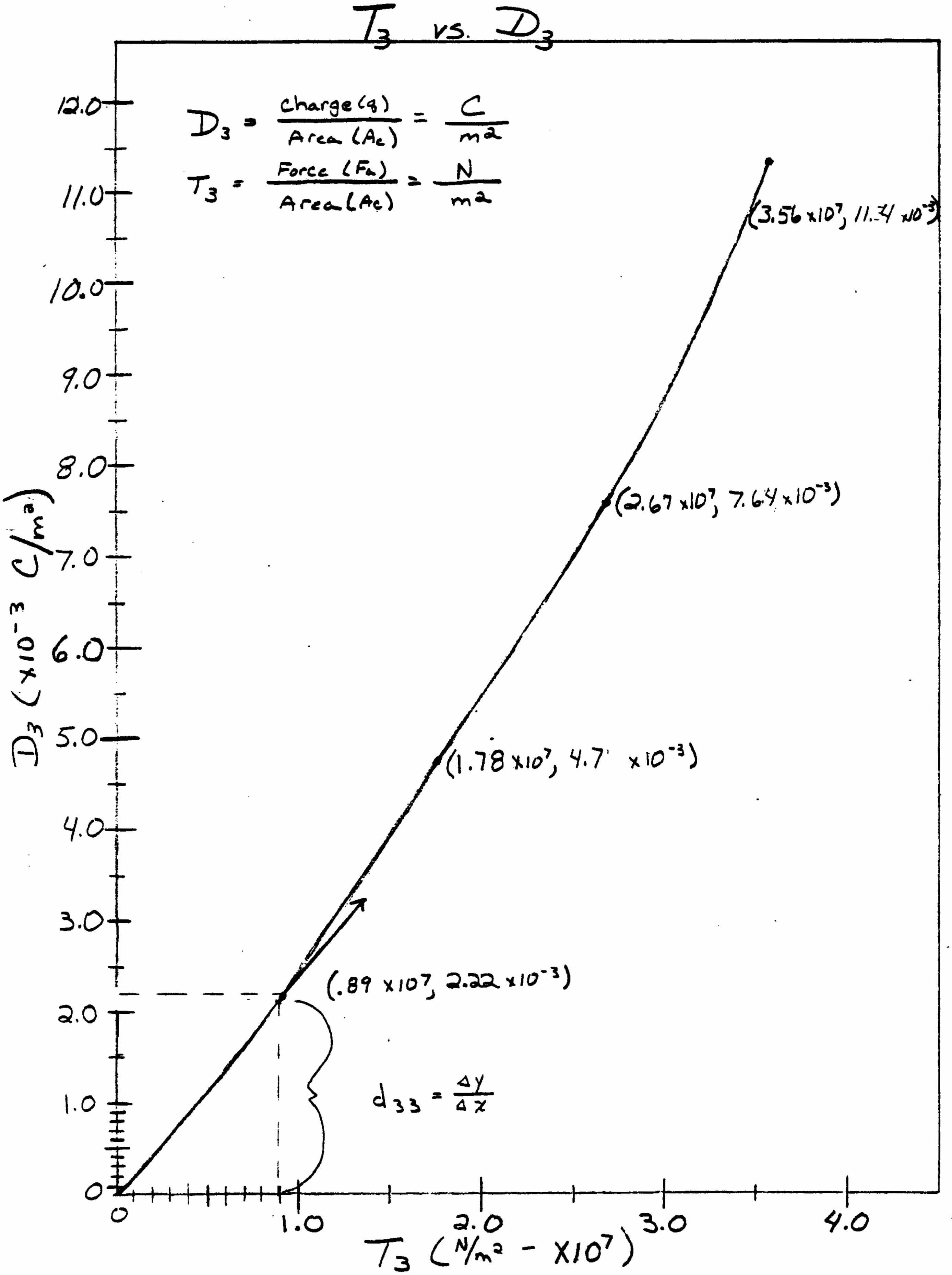
APPENDIX I



T3 vs. Capacitance
Capacitance (x 10^-10 F)
T3 (N/m2 → x 10^7)
(3.56 x10^7, 5.56 x10^-10)
(2.67x10^7, 5.4x10^-10)
(1.78x10^7, 4.98x10^-10)
(.89x10^7, 4.54x10^-10)
5.8
5.7
5.6
5.5
5.4
5.3
5.2
5.1
5.0
4.9
4.8
4.7
4.6
4.5
4.4
4.3
4.2
4.1
4.0
0
1.0
2.0
3.0
4.0



T_3 vs $\mathcal{E}_3$
$\mathcal{E}_3 = \frac{\text{Voltage } (e_o)}{\text{thickness } (t)} = \frac{V}{m}$
$T_3 = \frac{\text{Force } (F_a)}{\text{Area } (A_c)} = \frac{N}{m^2}$
$\mathcal{E}_3$ ($\times 10^5$ V/m)
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
Slope $\approx \frac{\mathcal{E}_3}{T_3} = (g_{33})_e$
0
1.0
T_3
2.0 ($N/m^2 \rightarrow \times 10^7$)
3.0
4.0



T_3 vs. D_3
$D_3 = \frac{\text{Charge }(q)}{\text{Area }(A_e)} = \frac{C}{m^2}$
$T_3 = \frac{\text{Force }(F_a)}{\text{Area }(A_e)} = \frac{N}{m^2}$
(3.56 x10⁷, 11.34 x10⁻³)
(2.67 x10⁷, 7.64 x10⁻³)
(1.78 x10⁷, 4.7 x10⁻³)
(.89 x10⁷, 2.22 x10⁻³)
$d_{33} = \frac{\Delta y}{\Delta x}$
D_3 (x10⁻³ C/m²)
T_3 (N/m² - X10⁷)
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0

Appendix II

Ceramic Ring Dimensions

Ring No.	Outside Diameter (meters)	Inside Diameter (meters)	Thickness ($m \times 10^{-3}$)	Area ($m^2 \times 10^{-4}$)
30	.02177	.0125	4.699	2.497
53	.0218	.0124	4.68	2.52
99	.0218	.0124	4.68	2.52
100	.0218	.0125	4.67	2.50
138	.0218	.0125	4.71	2.50
170	.02182	.0125	4.699	2.51
188	.0218	.01247	4.67	2.51
189	.0218	.0126	4.68	2.497
239	.0218	.0125	4.597	2.50
248	.0218	.0125	4.67	2.50
296	.02182	.0127	4.699	2.478
298	.02177	.01247	4.699	2.497

Appendix II Test Results - Voltage

	Ring Number	Voltage (volts) (at specified force levels)			
		500 lbs.	1000 lbs.	1500 lbs.	2000 lbs.
x	30	.056	.118	.165	.230
	53	.035	.056	.078	.138
	99	.055	.116	.179	.261
	100	.054	.117	.190	.271
	138	.057	.120	.184	.276
	170	.057	.119	.185	.272
	188	.056	.119	.186	.271
	189	.052	.118	.184	.266
*	239	.056	.120	.193	.287
x	248	.025	.072	.116	.167
x	296	.022	.073	.123	.193
	298	.049	.095	.198	.306

* used as representative ring in all examples

x broke

Appendix II

Test Results

(Capacitance and Dissipation Factor)

Ring	Capacitance (pF)				Dissipation factor			
No.	500 lbs.	1000 lbs.	1500 lbs.	2000 lbs.	500 lbs.	1000 lbs.	1500 lbs.	2000 lbs.
+ 30	490	508	516	528	NOT AVAILABLE			
53	478	487	498	501	.011	.013	.017	.028
99	492	507	524	536		NA		
100	490	506	521	530		NA		
138	486	498	512	530	.015	.019	.049	.078
170	495	505	501	513	.015	.020	.036	.072
188	492	495	512	520	.014	.021	.060	.071
189	490	508	526	551	.015	.019	.052	.073
239	454	498	540	556	.025	.031	.078	.130
+248	510	521	530	480	.021	.021	.030	.080
*296	470	465	485	496	.010	.014	.032	.132
298	488	496	520	542	.012	.028	.042	.135

* - broke

+ - broke at 2000 lbs. level